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RESEARCH MEMORANDUM

PERFORMANCE INVESTIGATION OF CAN-TYPE COMBUSTOR

II - WATER INJECTION AT VARIOUS STATIONS IN COMBUSTOR

By William P. Cook and Eugene V. Zettle

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

TECHNICAL EDITING WAIVED

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

September 30, 1948

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3.9. 95/3

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RESEARCH MEMORANDUM

PERFORMANCE INVESTIGATION OF CAN-TYPE COMBUSTOR

II - WATER INJECTION AT VARIOUS STATIONS IN COMBUSTOR

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SUMMARY

An investigation was made to determine the maximum quantity of water that could be injected either into or ahead of a single can-type combustor without reducing the attainable combustor-outlet temperature below the value required for engine operation and without the appearance of liquid water at the combustor outlet. The investigations were conducted at simulated conditions of military-rated engine speed of 7600 rpm, zero ram, and obtainable altitudes of 15,000 to 45,000 feet. Water was injected from spray nozzles at each of four stations: (1) ahead of the combustor, simulating injection ahead of the compressor in the engine; (2) into the upstream end of the combustor; (3) into the combustor halfway along its length; and (4) into the downstream end of the combustor.

The maximum total liquid-air ratio attainable without reducing the attainable combustor-outlet temperature below the required value for engine operation with water injection at each of the four stations at an altitude of 30,000 feet was: 0.065 at station 1; 0.044 at station 2; 0.097 at station 3; and 0.129 at station 4. With water injection at stations 3 or 4, however, liquid water passed through the combustor when the total liquid-air ratio exceeded a value of about 0.07. The results indicated that water injection at or near station 3 made possible the attainment of the highest total liquid-air ratios for the conditions at which the required combustor-outlet temperatures were attained and no liquid water appeared at the combustor outlet.

INTRODUCTION

Because a reaction motor has a low propulsive efficiency at low airspeeds, means of augmenting the thrust of some types of reaction motor for take-off and power spurts during flight are of interest. Various methods of augmenting the thrust of turbojet engines are being investigated at the NACA Cleveland laboratory. Thrust augmentation can be obtained by an increase in mass flow through the engine or by an increase in temperature that results in a higher jet velocity of the exhaust gases.

Three types of augmentation being considered are:

1. Liquid injection ahead of the compressor. Evaporation of the liquid produces lower temperatures throughout the compression cycle and increased air densities for the same engine rpm.

2. Liquid injection with air bleedoff ahead of the combustor. Liquid is injected ahead of the compressor and also injected directly into the combustor. The liquid injected into the combustor will be evaporated in the hot combustion products, thus requiring higher fuel-flow rates for the engine in order to maintain normal combustor-outlet temperatures. In addition, air is bledoff just ahead of the combustor in proportion to the quantity of liquid added in the combustor. The bleedoff air is directed to an auxiliary burner and burned with the stoichiometric quantity of fuel, resulting in a high-temperature, high-velocity auxiliary jet.

3. Tail-pipe burning. Tail-pipe burning consists in providing an auxiliary burner between the turbine outlet and exhaust nozzle of a turbojet engine. The additional combustion in the tail pipe heats the turbine exhaust gases to a temperature far above the maximum possible turbine-inlet temperatures. The increased temperature of the gases at the exhaust-nozzle inlet results in a substantially increased jet velocity.

The purpose of the investigation reported herein was to determine the maximum quantity of water that can be injected into or ahead of a single can-type combustor designed for a turbojet engine having a military rating of 4000 pounds thrust at a rotor speed of 7600 rpm and an 11-stage axial-flow compressor without resulting in insufficient energy output to drive the engine and without liquid water passing through the combustor.

Investigations were conducted at a simulated engine speed of 7600 rpm, zero ram, and obtainable simulated altitudes of 15,000 to 45,000 feet. The performance of this combustor without liquid injection is reported in reference 1.

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APPARATUS AND INSTRUMENTATION

One can-type combustor of a turbojet engine having a thrust rating of 4000 pounds and an 11-stage axial-flow compressor was connected to the laboratory air supply. The air temperature was controlled by a suitable preheater. Pressure and air flow in the combustor were manually regulated by valves located upstream and downstream of the combustor. The exhaust gases were cooled by water sprays before entering the laboratory altitude-exhaust system. Fuel, AN-F-32, Amendment-3, (JP-1), was introduced through a dual-control spray nozzle furnished by the manufacturer. Temperature of the incoming air was measured by two thermocouples in plane A-A. (See fig. 1.) Temperature of burner discharge gas was measured by 35 thermocouples in plane B-B, which is in the approximate position of the turbine. Three thermocouples were installed in plane C-C to determine whether combustion (afterburning) was present between planes B-B and C-C.

The apparatus is the same as that described in reference 1, with the following exceptions:

1. Spray nozzles injected water into the combustor at four different stations (fig. 1). Station 1 was located 62 inches upstream of the entrance diffuser on the combustor; stations 2, 3, and 4 were on planes 22, $13\frac{1}{4}$, and $4\frac{1}{2}$ inches, respectively, upstream of the combustor outlet. Water at station 1 was injected in the downstream direction from a single, centrally located, 80-gallon-per-hour, hollow-cone spray nozzle. At each of stations 2, 3, and 4, four nozzles were circumferentially installed 90° apart and so interconnected that either two opposing nozzles or all four nozzles could be used. Three nozzle sizes, 30-, 40-, or 60-gallons-per-hour, were used in conjunction with the two- or four-nozzle injection system to obtain the water-flow rates desired. The water flow was measured by calibrated rotameters.

2. The electric air preheater used in reference 1 was replaced by a gasoline preheater.

3. The chromel-alumel thermocouple junctions at plane B-B were covered with Inconel weld metal (fig. 2) to increase the operable life.

METHODS

Investigations were conducted on the combustor to determine the limiting amount of water injection at each of the four stations over a range of simulated altitudes from 15,000 to 45,000 feet at a simulated engine speed of 7600 rpm and zero ram pressure. Combustor 864
inlet-air conditions were maintained for each altitude and speed point selected at values determined from engine performance investigations made in the Cleveland altitude wind tunnel (reference 2). The required operating conditions from reference 2 are shown in figure 3. At each altitude investigated, water was added at one of the four injection stations until the combustor-outlet temperature required for engine operation without water injection at that point could not be maintained regardless of fuel flow or until combustion became unstable and blow-out occurred. The same procedure was followed for the other three injection stations. The water-injection limit was determined by either insufficient outlet temperature or no burning in the combustor.

The air flow, pressure, and temperature at the combustor inlet were maintained at the same values during the water-injection investigations as specified for burner operation without water addition, whereas the fuel-air ratio was increased to compensate for the cooling effect of the water injected.

RESULTS AND DISCUSSION

The gasoline inlet-air preheater used in these investigations consumed a maximum of 4.5 percent of the oxygen originally available in the air supply but had no apparent effect on the combustor operation. Combustion efficiency was the same using the electric inlet-air preheater as for the gasoline inlet-air preheater for the same inlet conditions of temperature, pressure, and velocity.

The maximum total liquid-air ratios and corresponding fuel-air ratios with water injection at the various stations and fuel-air ratios with no water injection for the can-type combustor operating at simulated conditions of zero ram, 7600 rpm, and various altitudes are shown in figure 4. The solid curves represent the water-injection limits; stable combustor operation is therefore obtained at altitudes and liquid-air ratios or fuel-air ratios to the left of the curves, whereas operation to the right of the curves results in insufficient combustor-outlet temperature or blow-out. The dashed curve shows the fuel-air ratio without water injection required at each altitude to give the required combustor-outlet temperature. Data at simulated altitudes below 15,000 feet were unobtainable due to limitations in the laboratory air-supply and exhaust facilities. The water-injection data presented are uncorrected for changes in humidity.

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A comparison of the curves of figure 4 is presented in figure 5. The following table presents the maximum total liquid-air ratios and the corresponding fuel-air ratios (from figs. 4 and 5) for water injection at each of the four stations at altitudes of 20,000, 30,000, and 40,000 feet. Also shown in the table are values of fuel-air ratio for no water injection at each of the three altitudes.

Water-injection station	Simulated altitude, ft					
	20,000		30,000		40,000	
	Liquid-air ratio	Fuel-air ratio	Liquid-air ratio	Fuel-air ratio	Liquid-air ratio	Fuel-air ratio
1	0.063	0.026	0.065	0.026	0.048	0.025
2	.046	.025	.044	.024	.043	.026
3	.10	.028	.097	.028	.066	.026
4	-------	-----	.129	.036	.094	.031
No water injection	-------	.019	-------	.020	-------	.021

The highest values of maximum total liquid-air ratio and the altitude at which it was obtained for water injection at each of the four stations in the altitude range investigated are presented in the following table:

Water-injection station	Highest value of maximum total liquid-air ratio in range investigated	Altitude for highest value of total liquid-air ratio, ft
1	0.066	29,500
2	.046	20,000 - 35,000
3	.110	22,500
4	.129	30,000

The comparatively low values of maximum total liquid-air ratio for injection at stations 1 and 2 indicate that the presence of water or water vapor at the upstream end of the combustor has an adverse effect upon combustion with injection directly into the combustion zone being more detrimental than injection upstream. (See figs. 6 and 7.) The injection of water further downstream in the combustor (stations 3 and 4) allows the attainment of higher liquid-air ratios without reducing the obtainable combustor-outlet temperature below the required value. With injection in station 4, the maximum total liquid-air ratio increased continually with decrease in altitude throughout the range of altitudes investigated (figs. 4(d) and 5); the investigation was not extended below simulated altitudes of 30,000 feet for reasons that will be subsequently discussed. At some of the higher liquid-air ratios with injection at stations 3 and 4, the water was not all vaporized before passing the plane corresponding to the turbine inlet in the engine (plane B-B), as is illustrated in figures 8 and 9. 864

Plots of the temperature distribution at the combustor outlet (plane B-B) are shown in figures 6 to 9 for representative altitudes with water injection at each of the four stations in quantities close to the maximum obtainable without reducing the combustor-outlet temperature below the required value. Also shown in figures 6 to 9 are outlet-temperature profiles obtained with no water injection. It was difficult to estimate the average combustor-outlet temperature during the course of the investigations; consequently, the average outlet temperatures shown are only approximately equal to the values required for nonaccelerating engine operation at the simulated flight conditions.

With water injection at stations 1 and 2 (figs. 6 and 7, respectively), there were no indications of liquid-water impingement on the thermocouples at the combustor outlet. With injection at station 3, however, the outlet temperature profiles (fig. 8) indicate water impingement on the thermocouples at all but the highest altitude (40,000 ft) for which the outlet-temperature-profile data are presented. The presence of liquid water at the combustor outlet is indicated in figures 8 and 9 by the shaded areas. Inside these shaded areas temperatures were usually less than 500° F, whereas the temperatures only a small fraction of an inch away were well above 1000° F. Temperatures inside the shaded regions are generally higher than the corresponding saturation temperatures because the thermocouples were alternately exposed to drops of water and to hot gases. For the conditions where the low thermocouple indications were encountered, liquid droplets were also visible through the downstream observation window. The high values of total liquid-air rates with water injection at station 3 indicated in figure 5 are therefore only obtainable with liquid water passing through the combustor.

With water injection at station 4, the outlet temperature profiles in figure 9(d) indicate passage of liquid water at a simulated altitude of 30,000 feet. No investigations were made to determine the injection limits at lower simulated altitudes because the quantities of liquid passing through the combustor appeared large when observed through the observation window, although the thermocouples at the combustor outlet indicated liquid-water passage through only a small portion of the outlet duct. The combustor-outlet thermocouple readings therefore do not afford an adequate indication of the presence of liquid water at the combustor outlet.

The maximum total liquid-air ratios attainable without reducing the average combustor-outlet temperature below the required value were therefore considerably in excess of those liquid-air ratios where liquid water appeared at the combustor outlet when the water was injected at stations 3 or 4. With injection at these stations, liquid water passed through the combustor when the total liquid-air ratio exceeded a value of about 0.07. With water injection at stations 1 or 2, however, there was no indication of liquid water at the combustor outlet.

The results indicate that the injection of water at station 3 gave the highest total liquid-air ratios for the conditions at which the required combustor-outlet temperatures are attained and no liquid water appears at the combustor outlet.

The water-injection rates and the fuel-injection rates are presented in figures 10 and 11, respectively, for operation of the combustor at various altitudes with water injection at each of the four stations at the maximum rate attainable without reduction of the combustor-outlet temperature below the required value. The fuel-flow rates necessary with no water injection to give the required combustor-outlet temperatures are shown in figure 11.

SUMMARY OF RESULTS

The results obtained in the investigation of a can-type combustor at conditions simulating zero ram, 7600 rpm, various altitudes, and with water injection at each of the following four stations are summarized: station 1, 62 inches upstream of entrance diffuser on combustor; station 2 (at upstream end of liner) 22 inches upstream of outlet flange of combustor; station 3 (approximately halfway down liner) $13\frac{1}{4}$ inches upstream of outlet flange of combustor; and station 4 (near outlet from liner) $4\frac{1}{2}$ inches upstream of outlet flange of combustor.

1. The maximum total liquid-air ratios attainable without reduction of the attainable combustor-outlet temperatures below the values required for engine operation were:

Water-injection station	Simulated altitude, ft					
	20,000		30,000		40,000	
	Liquid-air ratio	Fuel-air ratio	Liquid-air ratio	Fuel-air ratio	Liquid-air ratio	Fuel-air ratio
1	0.063	0.026	0.065	0.026	0.048	0.025
2	.046	.025	.044	.024	.043	.026
3	.10	.028	.097	.028	.066	.026
4	-------	-----	.129	.036	.094	.031
No water injection	-------	.019	-------	.020	-------	.021

2. With water injection at stations 1 or 2, no indications of liquid water at the combustor outlet were present.

3. With water injection at stations 3 or 4, liquid water passed through the combustor when the total liquid-air ratio exceeded a value of about 0.07 in the altitude range investigated.

4. The results indicated that water injection at or near station 3 made possible the attainment of the highest total liquid-air ratios for the conditions at which the combustor-outlet temperatures were attained and no liquid water appeared at the combustor outlet.

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National Advisory Committee for Aeronautics,
Cleveland, Ohio.

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1. Zettle, Eugene V., and Cook, William P.: Performance Investigation of Can-Type Combustor. I - Instrumentation, Altitude Operational Limits and Combustion Efficiency. NACA RM No. E8F17, 1948.

2. Fleming, William A.: Altitude-Wind-Tunnel Investigation of a 4000-Pound-Thrust Axial-Flow Turbojet Engine. I - Performance and Windmilling Drag Characteristics. NACA RM No. E8F09, 1948.

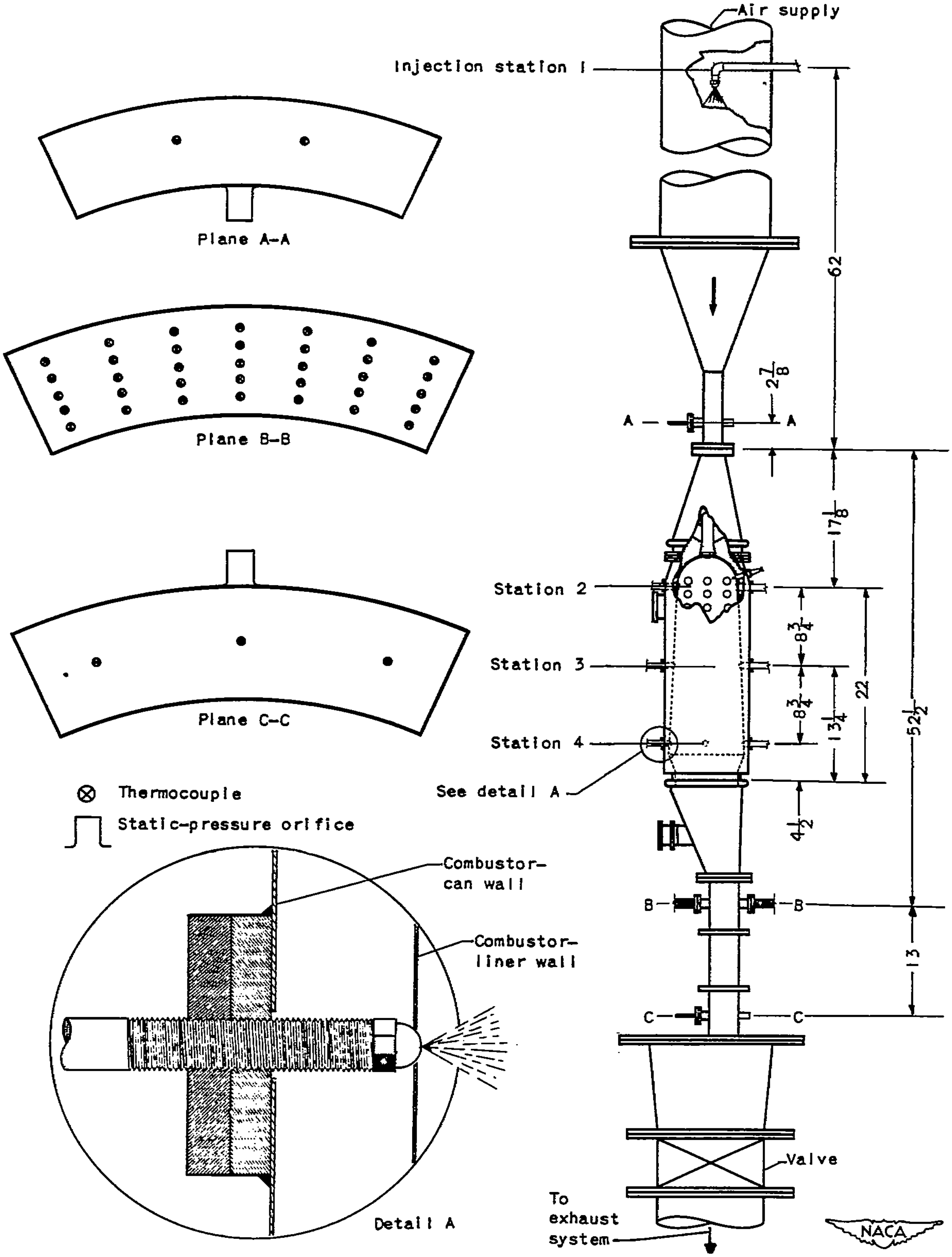

Figure 1. - Diagram showing test rig and instrumentation positions used in water-injection investigation of can-type combustor. (Dimensions given in inches.)

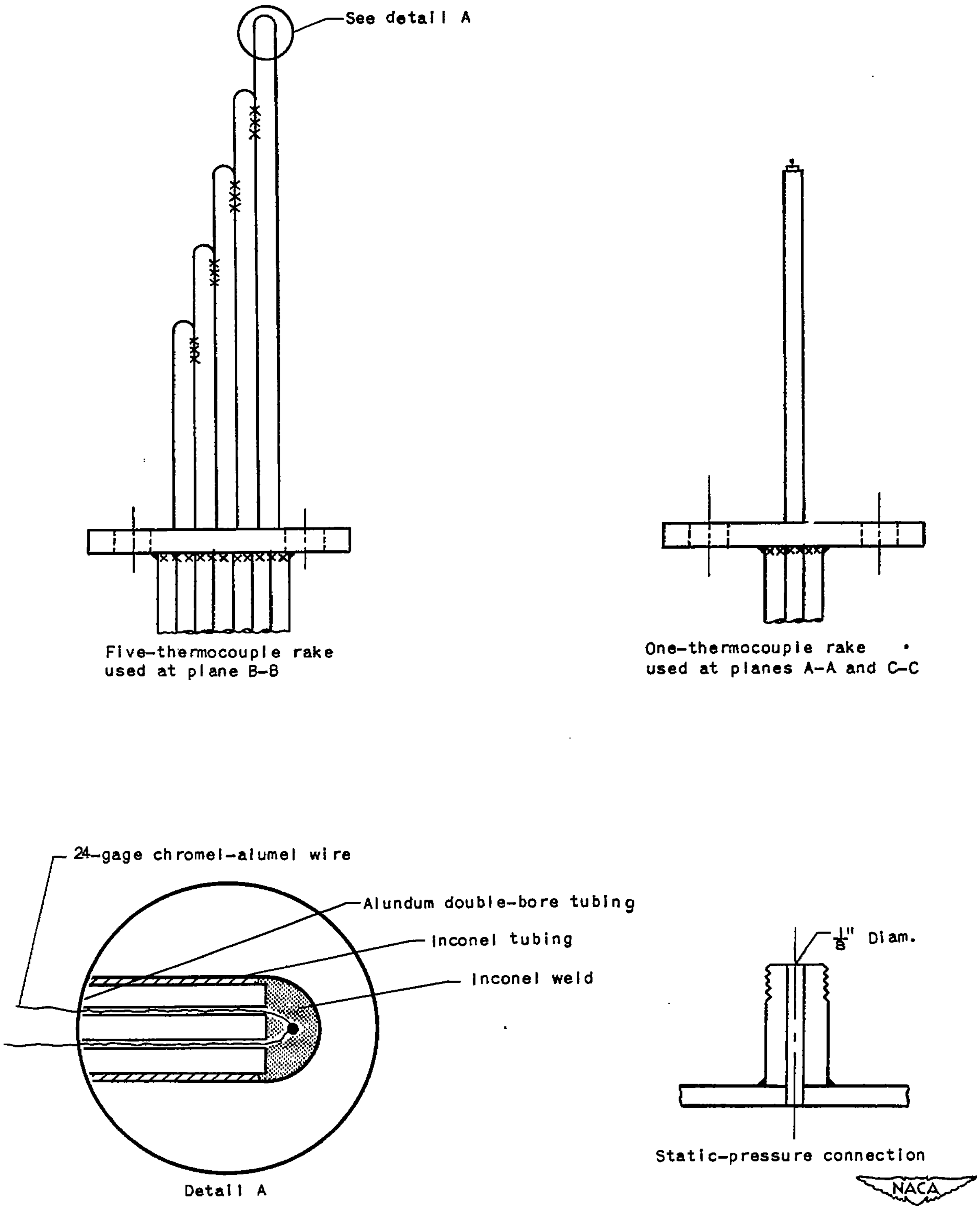

Figure 2. - Details of instrumentation used in water-injection investigation of can-type combustor.

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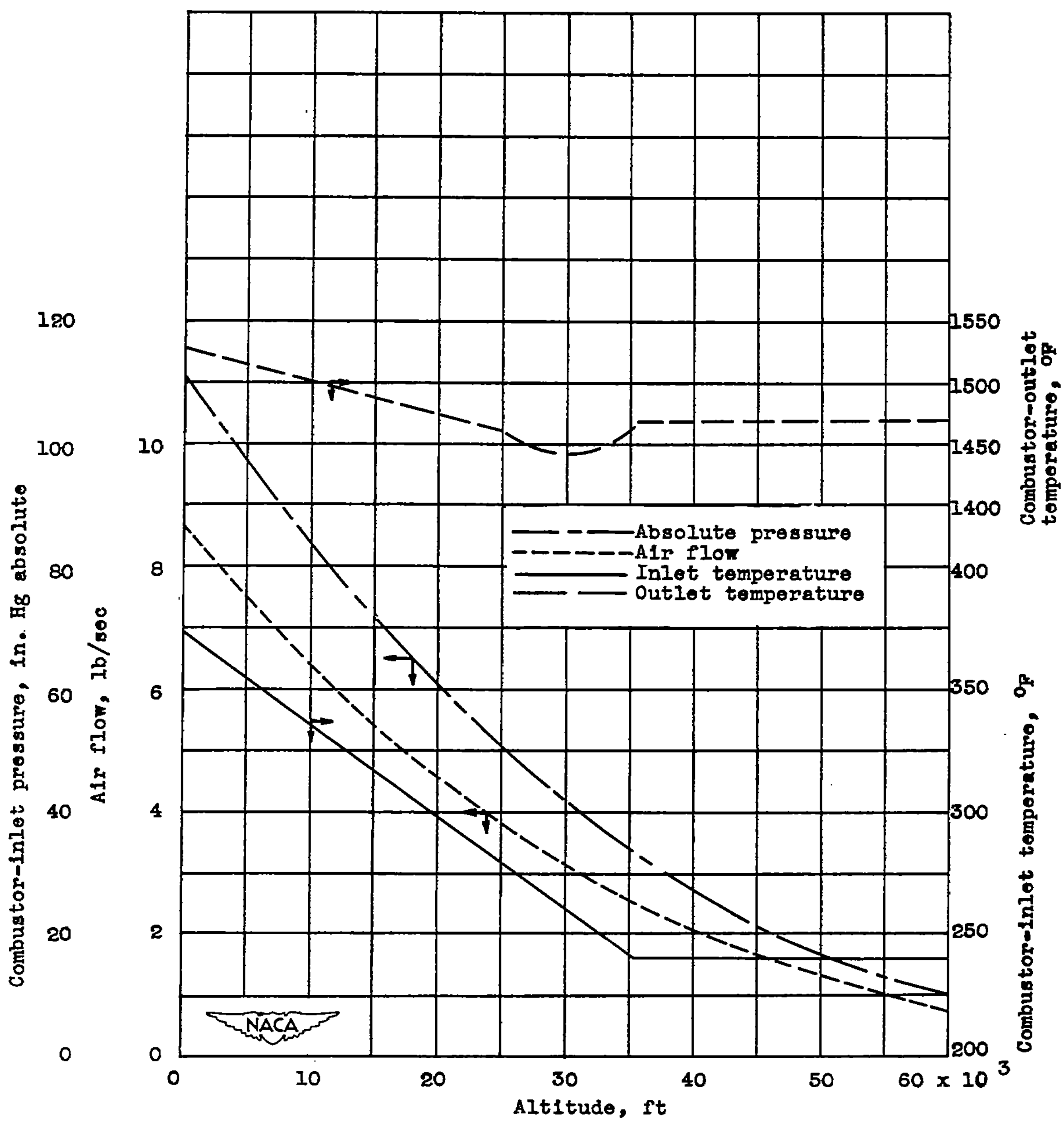

Figure 3. - Operating conditions of can-type combustor for various altitudes at rated engine speed of 7600 rpm and zero ram. (Data from reference 2.)

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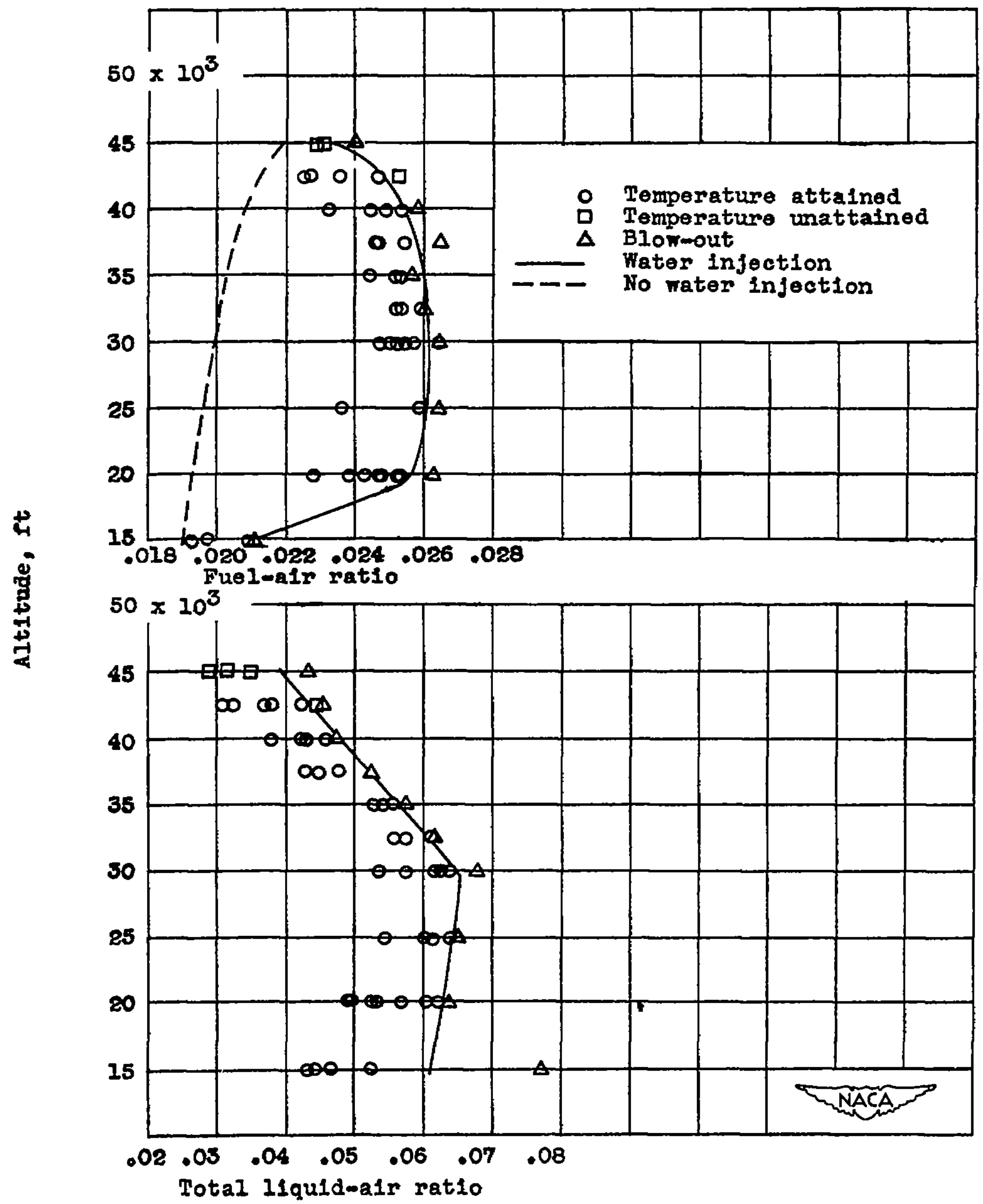

(a) Water injection at station 1.

Figure 4. - Effect of altitude on total liquid-air ratio and on fuel-air ratio with and without water injection in can-type combustor operating at simulated conditions of zero ram and 7600 rpm.

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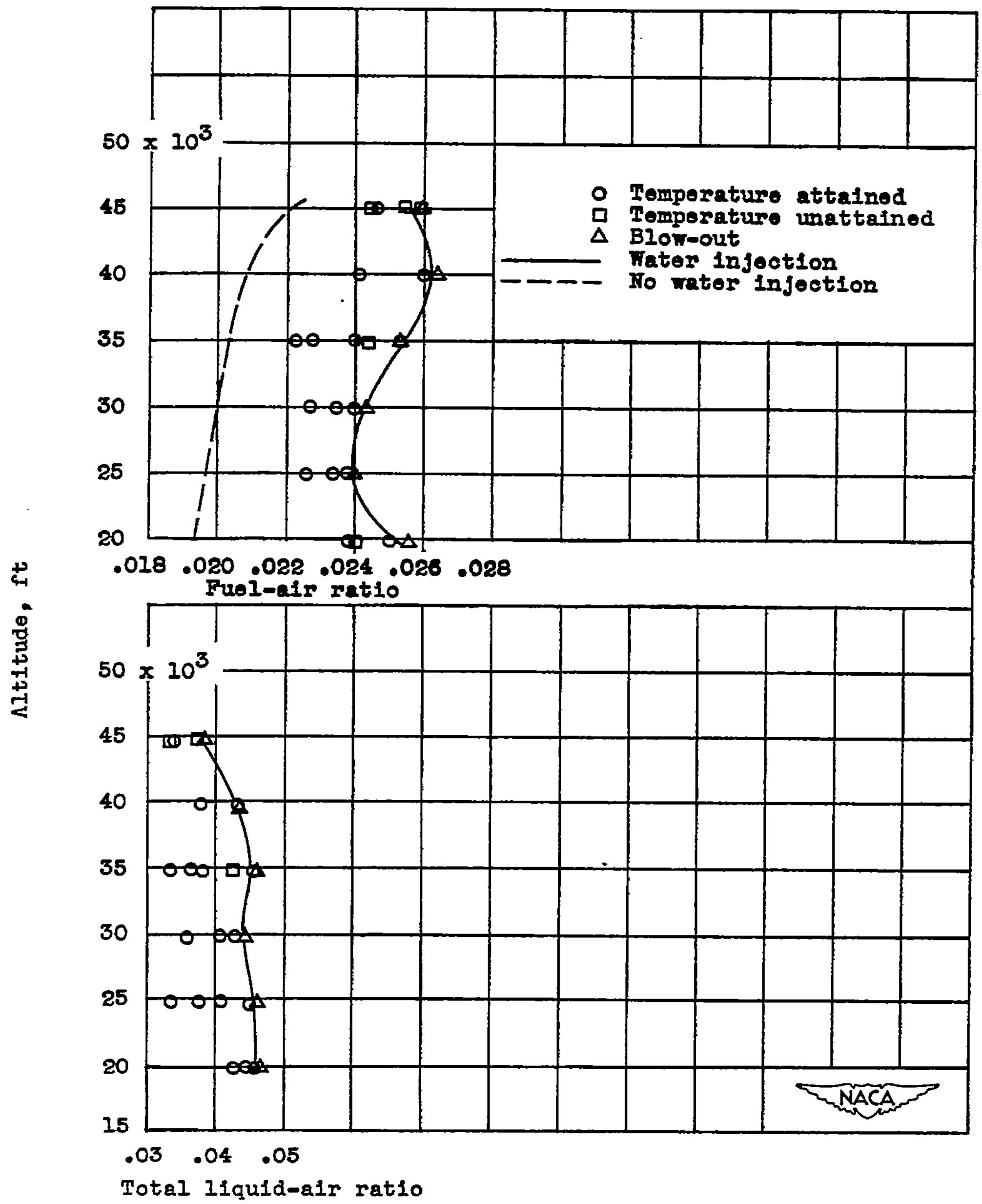

(b) Water injection at station 2.

Figure 4. – Continued. Effect of altitude on total liquid-air ratio and on fuel-air ratio with and without water injection in can-type combustor operating at simulated conditions of zero ram and 7600 rpm.

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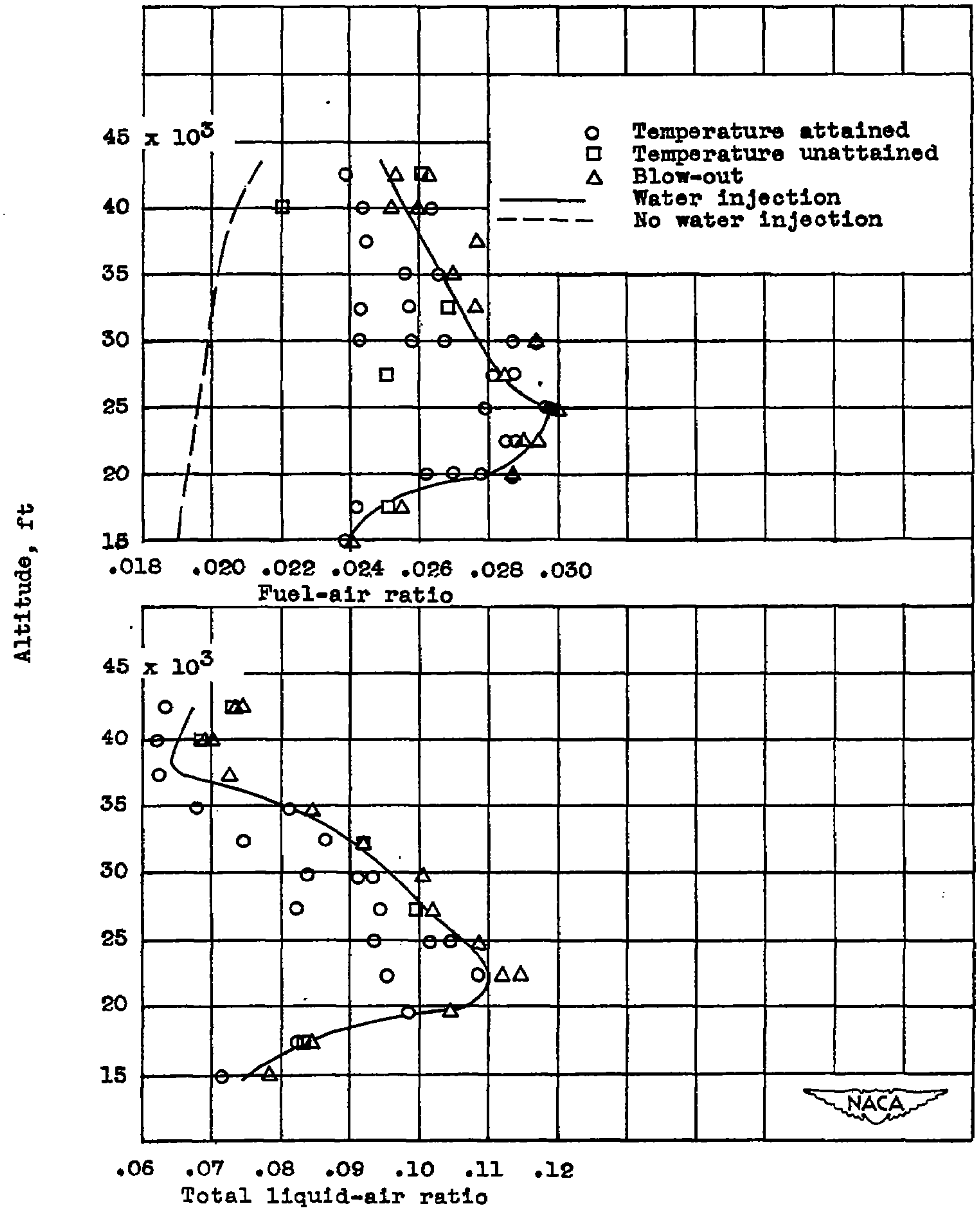
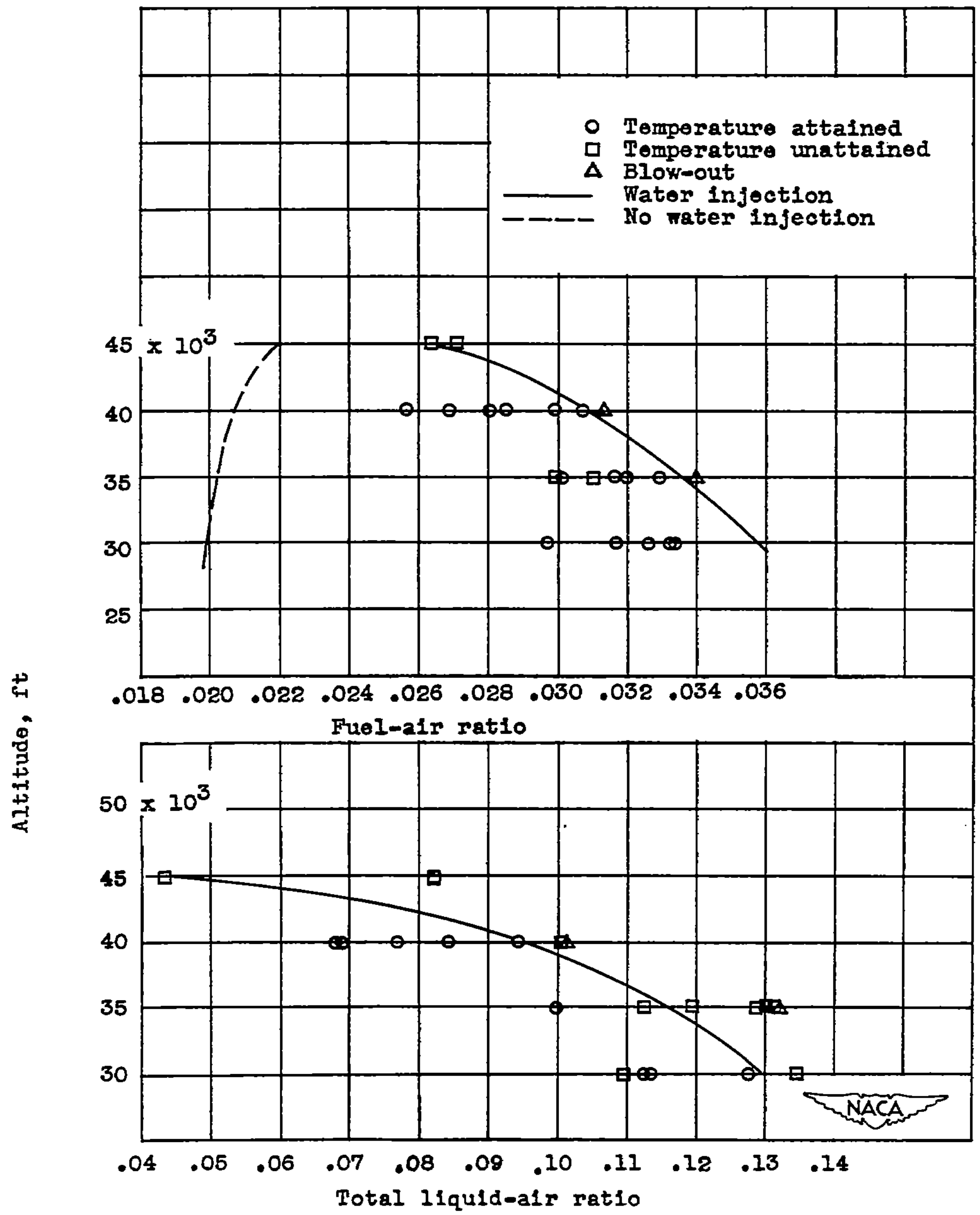


(c) Water injection at station 3.

Figure 4. – Continued. Effect of altitude on total liquid-air ratio and on fuel-air ratio with and without water injection in can-type combustor operating at simulated conditions of zero ram and 7600 rpm.



(d) Water injection at station 4.

Figure 4. - Concluded. Effect of altitude on total liquid-air ratio and on fuel-air ratio with and without water injection in can-type combustor operating at simulated conditions of zero ram and 7600 rpm.

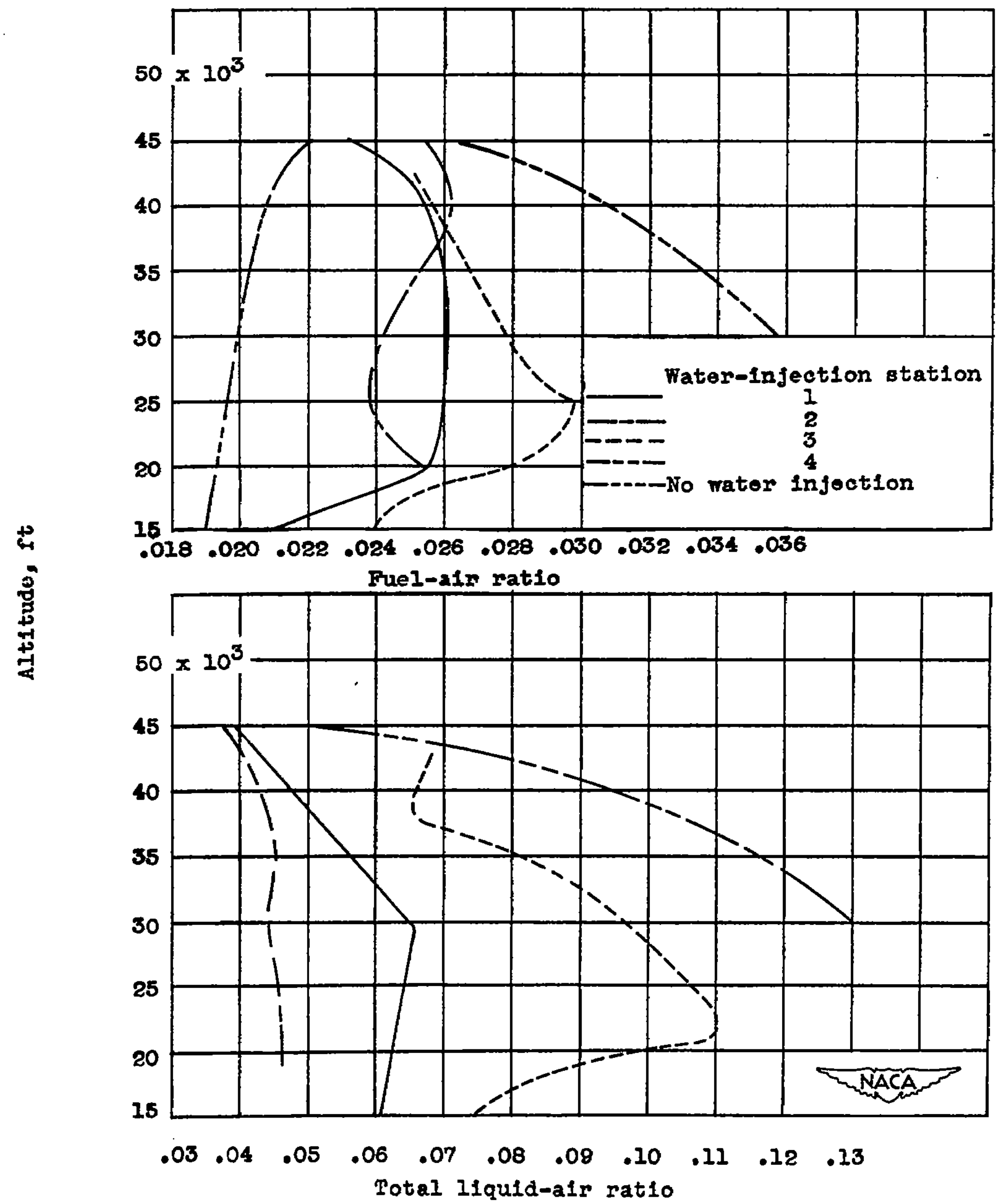
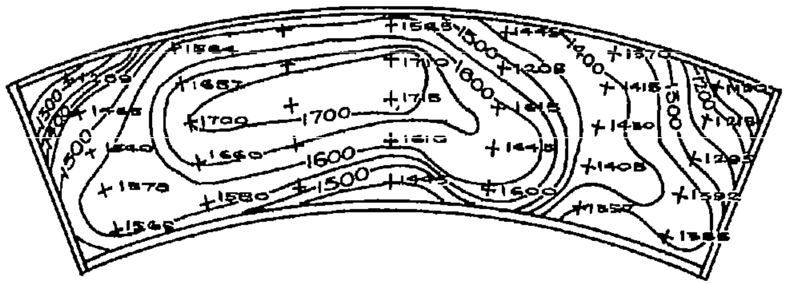
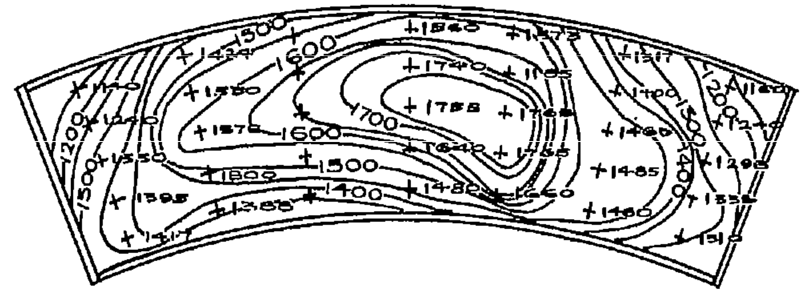


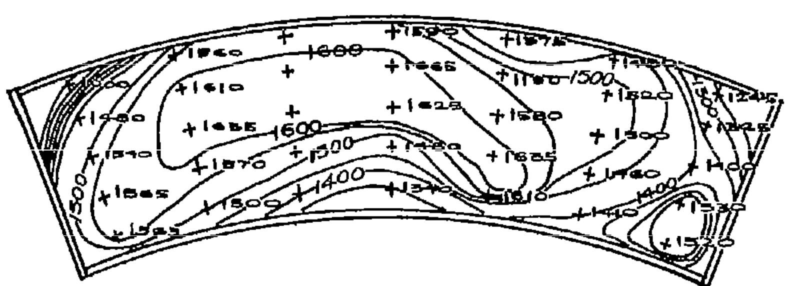
Figure 5. – Effect of altitude on maximum total liquid-air ratios with water injection at various stations and corresponding fuel-air ratios for can-type combustor operating at simulated conditions of zero ram and 7600 rpm.



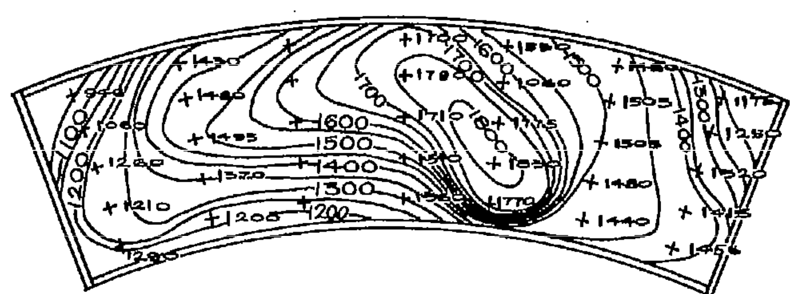
(a) Altitude, 42,500 feet; average temperature, 1485° F; without water injection.



(b) Altitude, 42,500 feet; average temperature, 1451° F; at water-injection limit: water flow, 129 pounds per hour; liquid-to-air ratio, 0.0446.

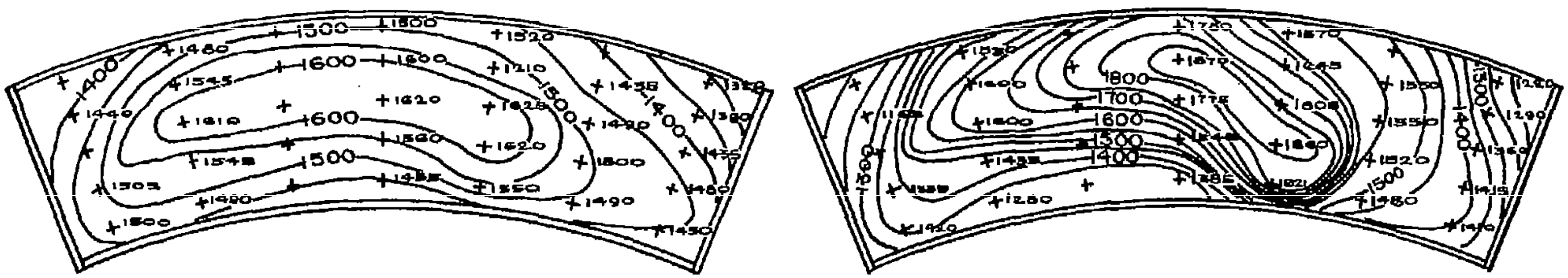


(c) Altitude, 30,000 feet; average temperature, 1483° F; without water injection.



(d) Altitude, 30,000 feet; average temperature, 1427° F; at water-injection limit: water flow, 299 pounds per hour; liquid-to-air ratio, 0.0678.

Figure 6. - Temperature-distribution pattern for limiting water-injection conditions at station I and operating conditions required to obtain same temperature rise with fuel alone at simulated engine speed of 7600 rpm and zero ram.



(e) Altitude, 20,000 feet; average temperature, 1495° F; without water injection.

(f) Altitude, 20,000 feet; average temperature, 1512° F; at water-injection limit: water flow, 420 pounds per hour; liquid-to-air ratio, 0.0625.

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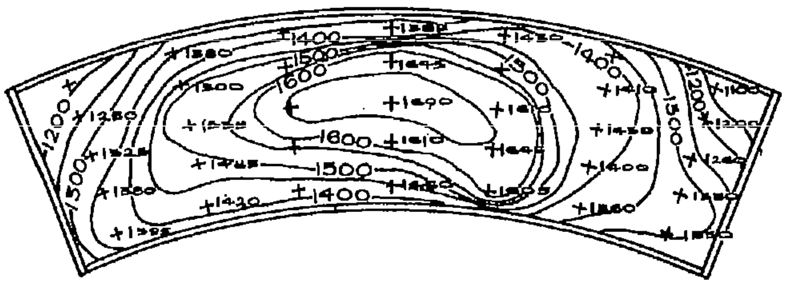
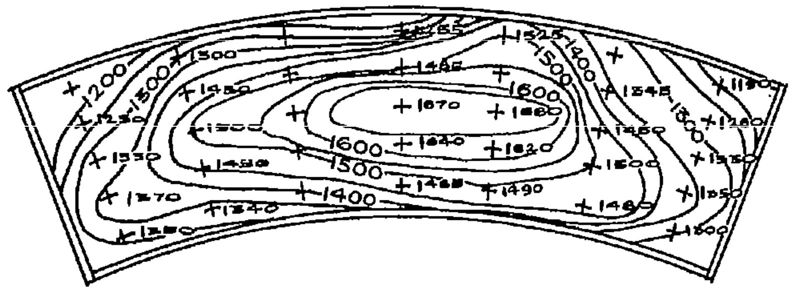
Figure 6. - Concluded. Temperature-distribution pattern for limiting water-injection conditions at station 1 and operating conditions required to obtain same temperature rise with fuel alone at simulated engine speed of 7600 rpm and zero ram.



(a) Altitude, 45,000 feet; average temperature, 1429° F; without water injection.



(b) Altitude, 45,000 feet; average temperature, 1421° F; at water-injection limit: water flow, 73 pounds per hour; liquid-to-air ratio, 0.0379.

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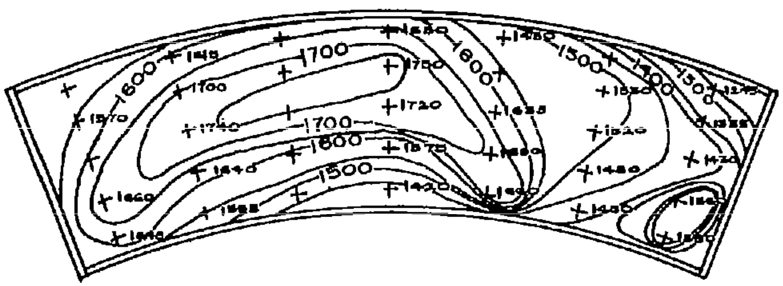
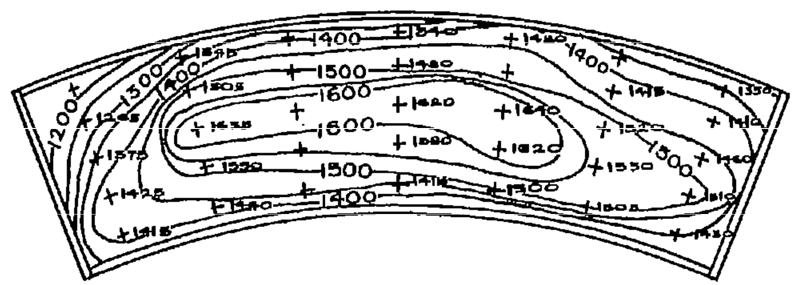
[redacted]

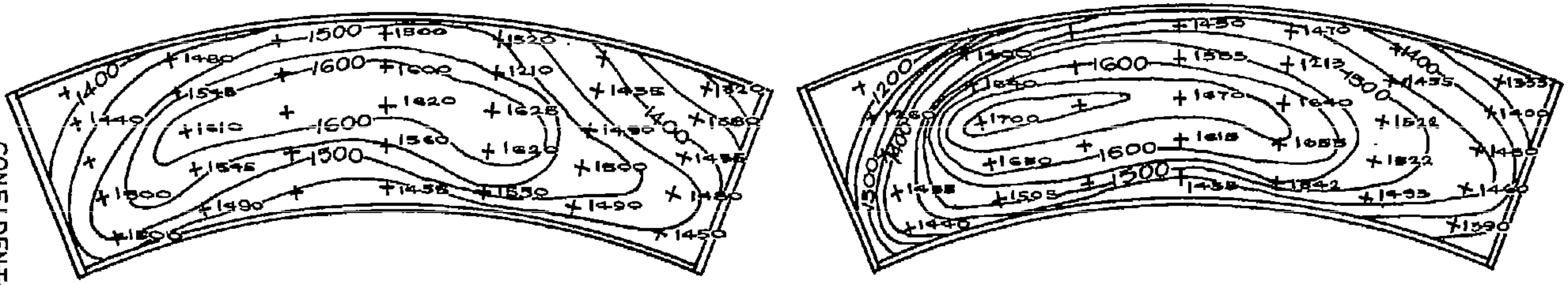


(c) Altitude, 30,000 feet; average temperature, 1568° F; without water injection.



(d) Altitude, 30,000 feet; average temperature, 1473° F; at water-injection limit: water flow, 221 pounds per hour; liquid-to-air ratio, 0.0432.

Figure 7. - Temperature-distribution pattern for limiting water-injection conditions at station 2 and operating conditions required to obtain same temperature rise with fuel alone at simulated engine speed of 7600 rpm and zero ram.



(e) Altitude, 20,000 feet; average temperature, 1494° F; without water injection.

(f) Altitude, 20,000 feet; average temperature, 1489° F; at water-injection limit: water flow, 335 pounds per hour; liquid-to-air ratio, 0.045.

Figure 7. - Concluded. Temperature-distribution pattern for limiting water-injection conditions at station 2 and operating conditions required to obtain same temperature rise with fuel alone at simulated engine speed of 7600 rpm and zero ram.

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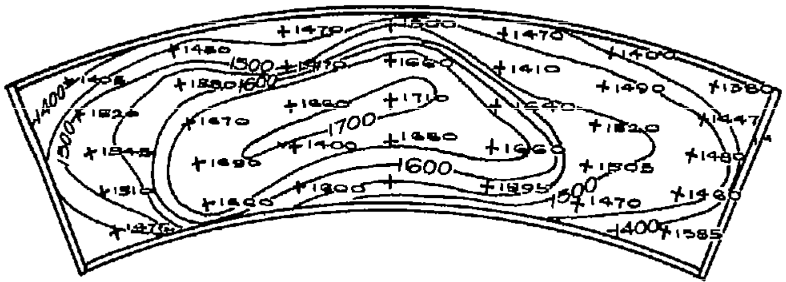
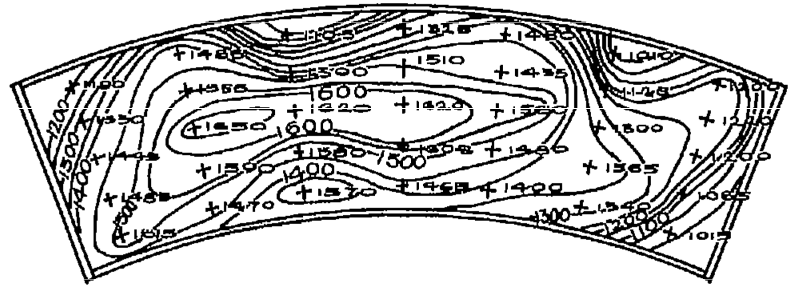
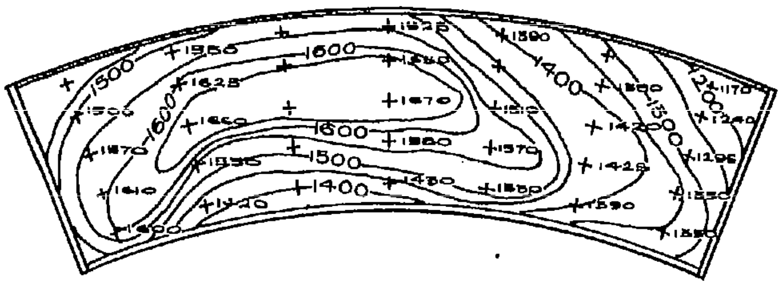


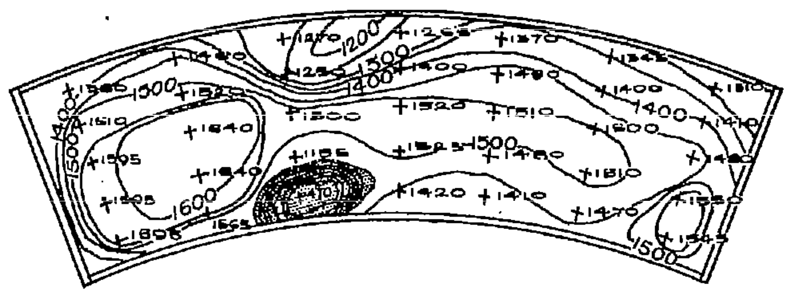
(a) Altitude, 40,000 feet; average temperature, 1528° F; without water injection.



(b) Altitude, 40,000 feet; average temperature, 1383° F; at water-injection limit: water flow, 317 pounds per hour; liquid-to-air ratio, 0.07.

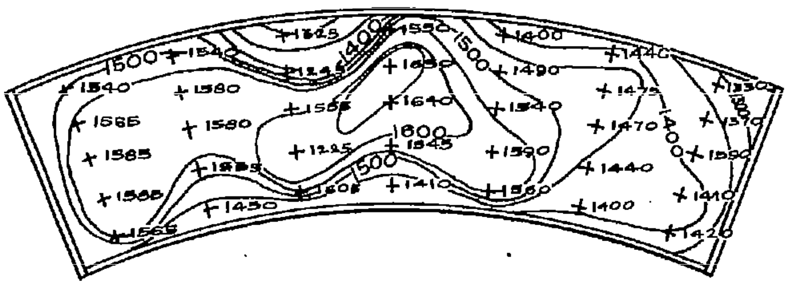


(c) Altitude, 35,000 feet; average temperature, 1479° F; without water injection.

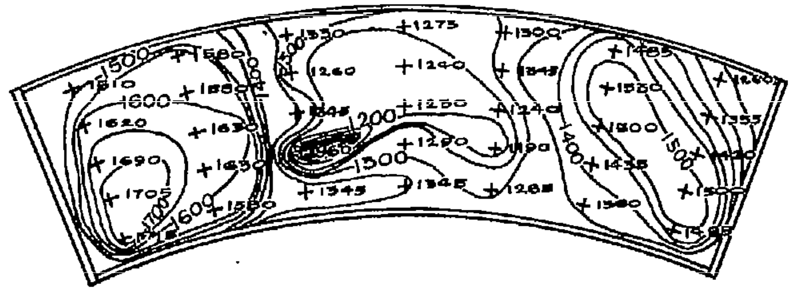


(d) Altitude, 35,000 feet; average temperature, 1430° F; at water-injection limit: water flow, 548 pounds per hour; liquid-to-air ratio, 0.084.

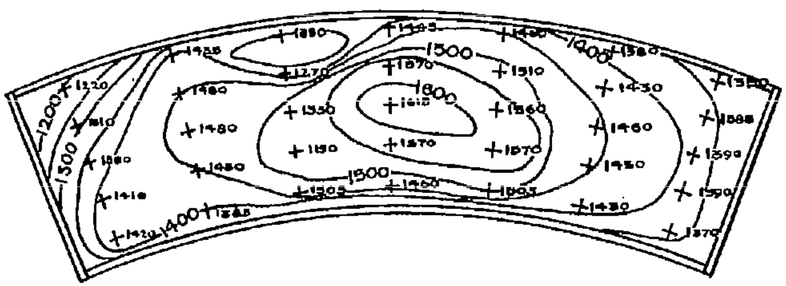
Figure 8. - Temperature-distribution pattern at station 3 for limiting water-injection conditions and operating conditions required to obtain same temperature rise with fuel alone at simulated engine speed of 7600 rpm. (Pattern for (i) and (j) were unobtainable without water injection.)



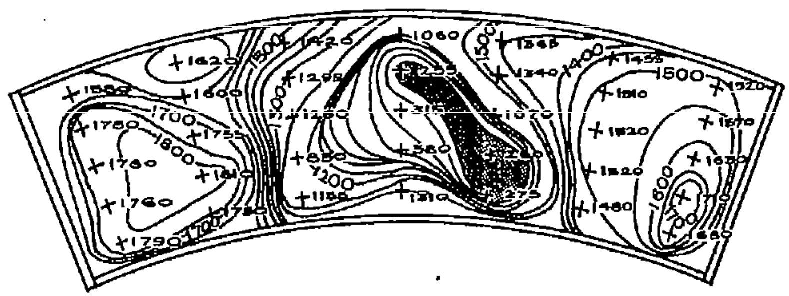
(e) Altitude, 27,500 feet; average temperature, 1486° F; without water injection.



(f) Altitude, 27,500 feet; average temperature, 1416° F; at water-injection limit: water flow, 898 pounds per hour; liquid-to-air ratio, 0.099.

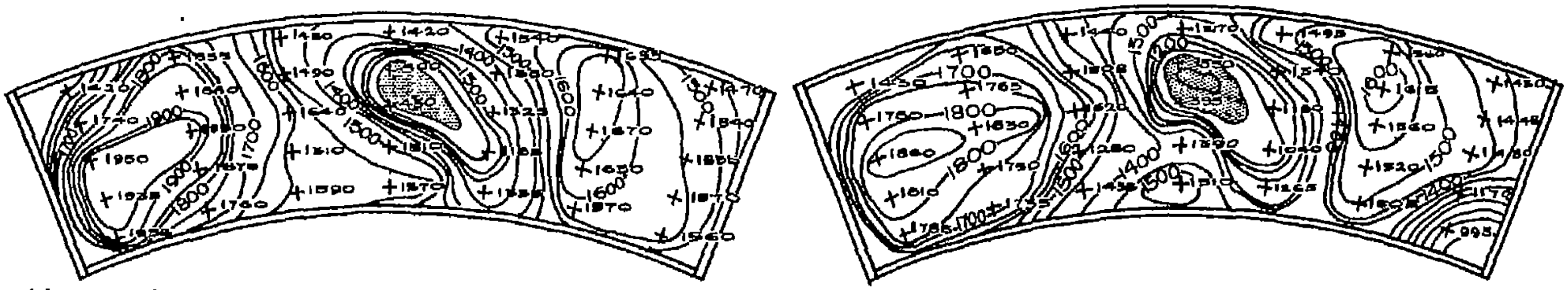


(g) Altitude, 22,500 feet; average temperature, 1432° F; without water injection.



(h) Altitude, 22,500 feet; average temperature, 1325° F; at water-injection limit: water flow, 1205 pounds per hour; liquid-to-air ratio, 0.1086.

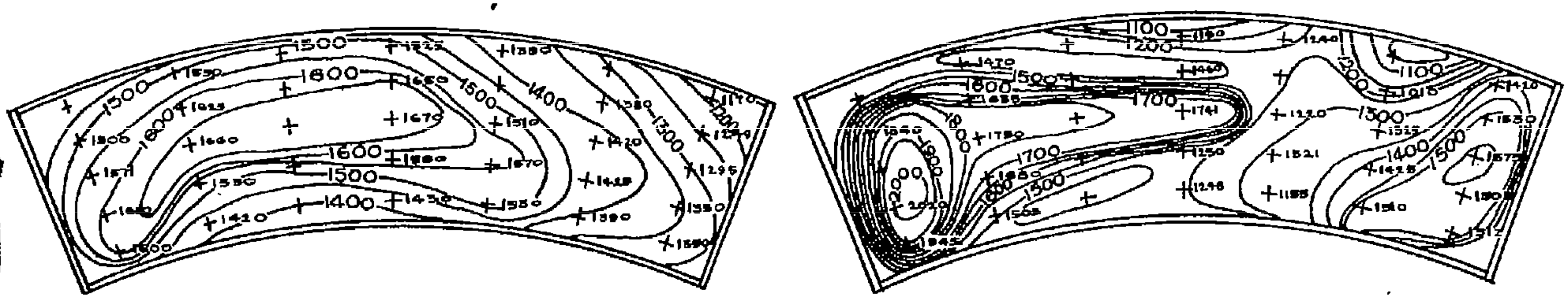
Figure 8. - Continued. Temperature-distribution pattern at station 3 for limiting water-injection conditions and operating conditions required to obtain same temperature rise with fuel alone at simulated engine speed of 7600 rpm. (Patterns for (i) and (j) were unobtainable without water injection.)



(i) Altitude, 15,000 feet; average temperature, 1535° F; at water-injection limit: water flow, 1005 pounds per hour; liquid-to-air ratio, 0.0742.

(j) Altitude, 15,000 feet; average temperature, 1432° F; at water-injection limit: water flow, 1088 pounds per hour; liquid-to-air ratio, 0.0783.

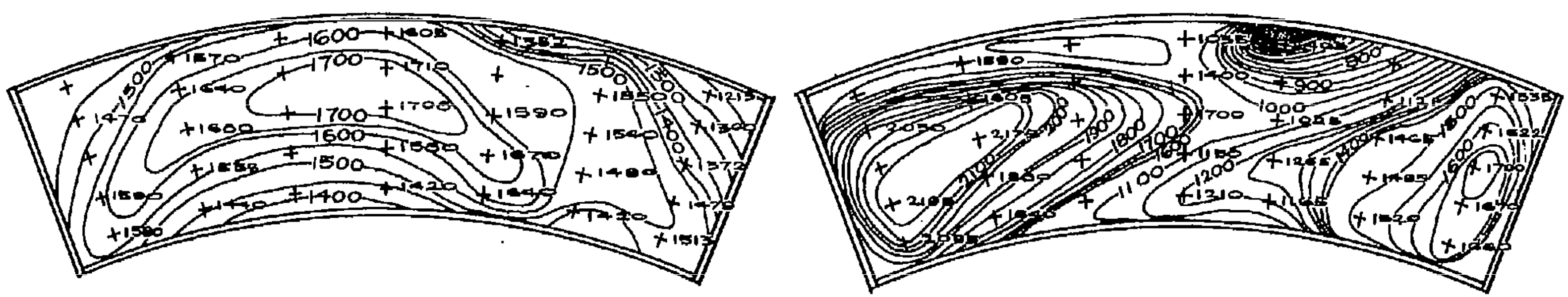
Figure 8. - Concluded. Temperature-distribution pattern at station 3 for limiting water-injection conditions and operating conditions required to obtain same temperature rise with fuel alone at simulated engine speed of 7600 rpm. (Patterns for (i) and (j) were unobtainable without water injection.)



(a) Altitude, 35,000 feet; average temperature, 1479° F; without water injection.

(b) Altitude, 35,000 feet; average temperature, 1479° F; at water-injection limit: water flow, 827 pounds per hour; liquid-to-air ratio, 0.1195.

Figure 9. – Temperature-distribution pattern for limiting water-injection conditions at station 4 and operating conditions required to obtain same temperature rise with fuel alone at simulated engine speed of 7600 rpm and zero ram.



(c) Altitude, 30,000 feet; average temperature, 1525° F; without water injection.

(d) Altitude, 30,000 feet; average temperature, 1532° F; at water-injection limit: water flow, 1200 pounds per hour; liquid-to-air ratio, 0.1346.

Figure 9. - Concluded. Temperature-distribution pattern for limiting water-injection conditions at station 4 and operating conditions required to obtain same temperature rise with fuel alone at simulated engine speed of 7600 rpm and zero ram.

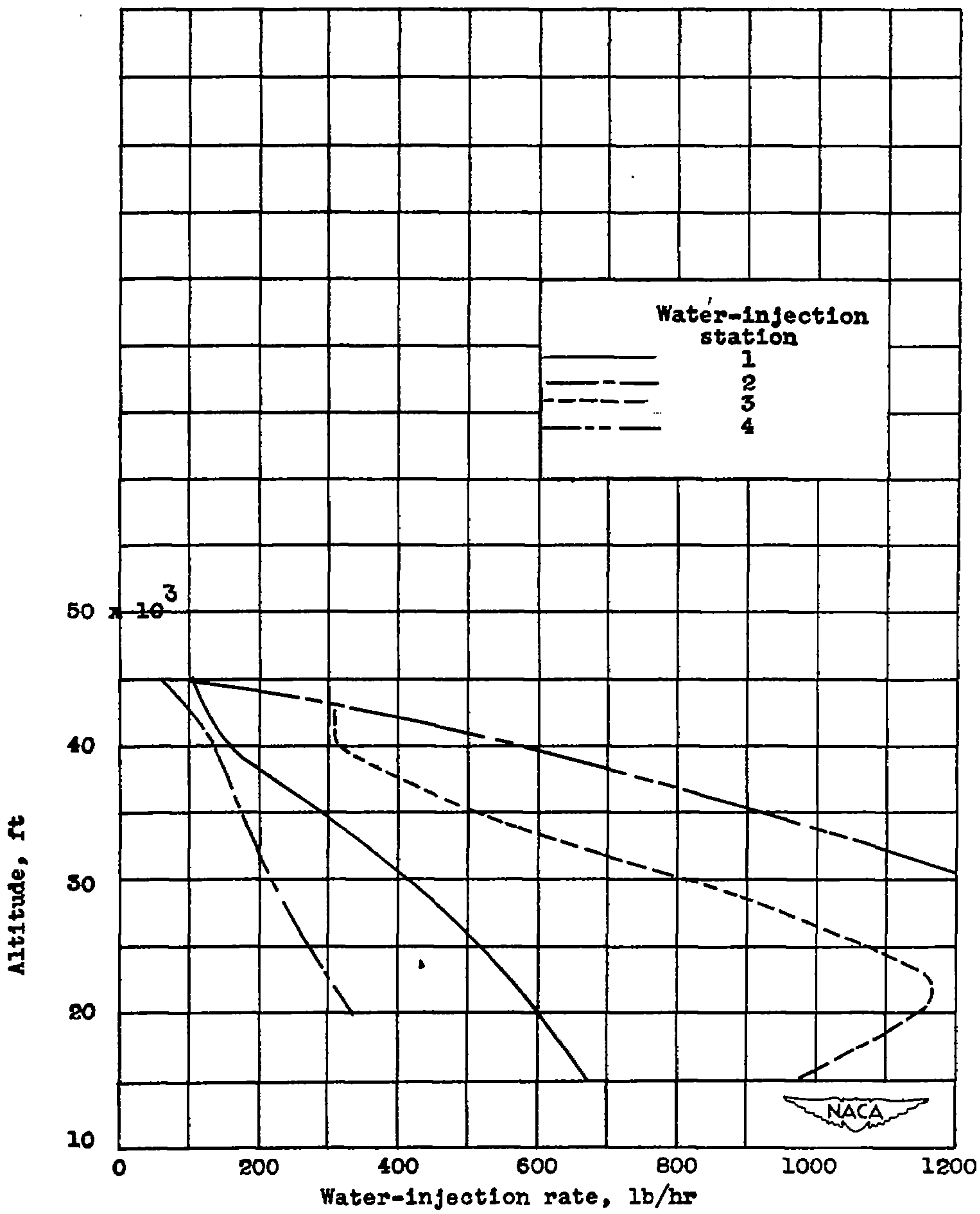


Figure 10. - Effect of altitude on water-injection rates at various stations for can-type combustor operating at simulated conditions of zero ram and 7600 rpm.

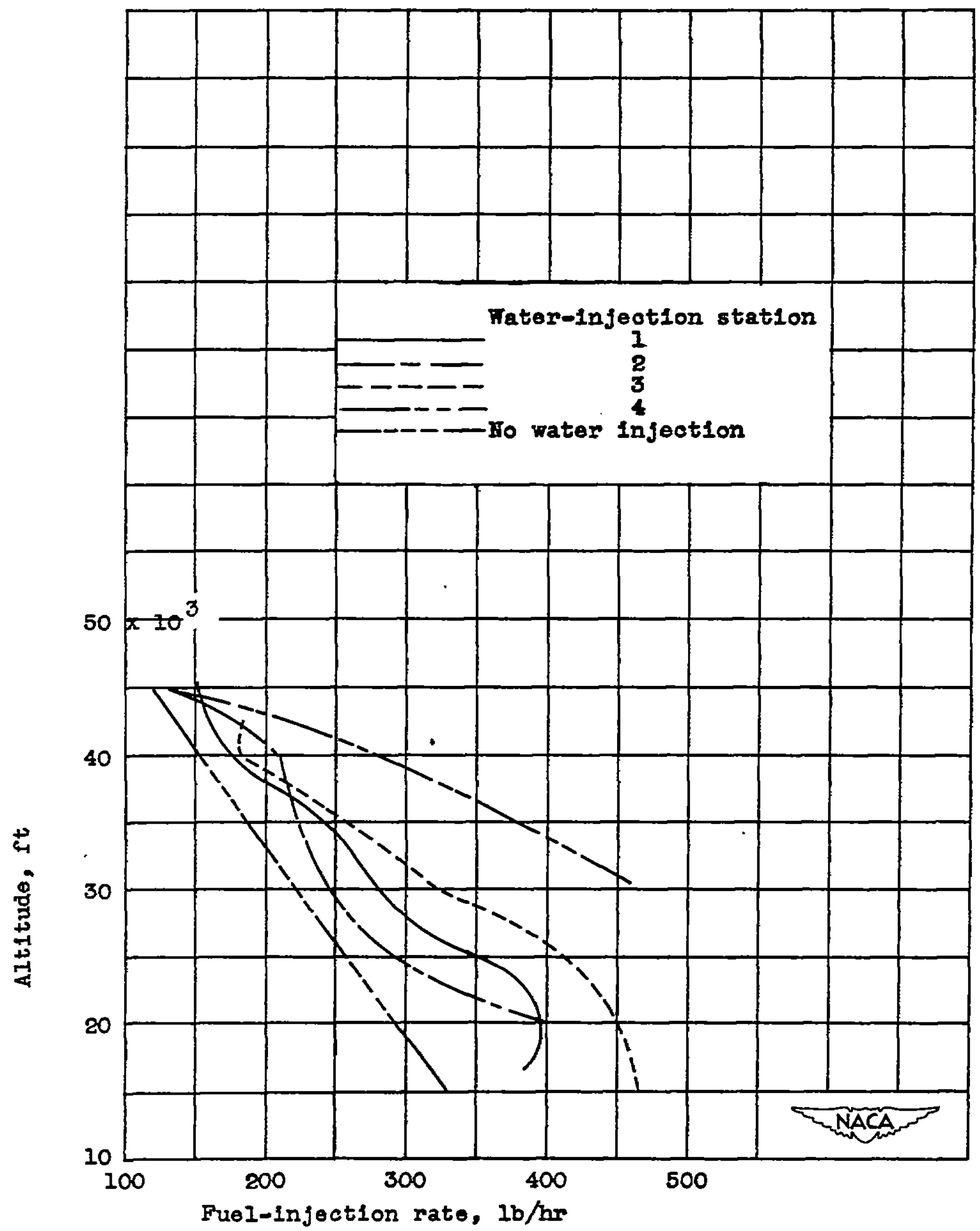


Figure 11. - Effect of altitude on fuel-injection rates with no water injection and with maximum water injection at various stations for can-type combustor operating at simulated conditions of zero ram and 7600 rpm.